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T. L. AGGSON
T. L. SKILLMAN

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

Direct measurements of electric fields were made in the outer magnetosphere during two sudden commencements in 1972. These measurements were observed with the double floating probe experiment carried aboard the IMP 6 satellite. The initial variations of the measured electric field consisted of an increase from a background of about 1 mv/meter to some 10 mv/meter at about 7 r_E (earth radii) and to some 4 mv/meter at 3 r_E. These initial electric field disturbances were longitudinal, oriented counter clockwise about an axis pointed north. A solution of Maxwell's third equation, $\vec{\nabla} \times \vec{E} = -\partial \vec{B} / \partial t$, is derived for these measurements using a quasi-static version of Mead's model of the magnetosphere B (t). This solution seems to describe well the magnitude and direction of the initial perturbation of the electric field vectors observed during these two sudden commencements. After the initial increase, the measured electric field rings several times with periods of the order of minutes. This observed oscillatory behavior correlates nicely with magnetic observatory records taken near the foot of the magnetic field line passing through the satellite. Using the above solution E (t) as the original perturbation, the amplitude of these oscillations can be extrapolated as guided transverse Alfvén waves from the equatorial region to the ionosphere yielding an analytical expression which predicts well the magnitude of the latitude variation of the horizontal disturbance at ground level.

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INTRODUCTION

Several days after a large solar disturbance there often occurs a sudden increase in the horizontal magnetic field intensity which is observed to occur simultaneously to within a minute or so of time at all magnetic observations. The larger of these sudden commencements (SC's) often precede a major magnetic storm. These events have been studied experimentally now for nearly a century (see Chapman and Bartels, 1940, pp. 296-299 for a discussion of the more important early investigations). A classical paper by Chapman and Ferraro (1931) gave a viable interpretation of the SC in terms of the effect of an impact of a solar gas stream on the geomagnetic field. Gold (1955) later improved on this explanation suggesting a shock wave propagating through an interplanetary plasma as the origin of the SC, and Dessler (1958) considered the transmission of the impact of the SC from the magnetopause to ground level in terms of hydromagnetic waves. Wilson and Sugiura (1961) then observed that this transmission was via longitudinal waves at low latitude and by transverse waves at higher geomagnetic latitudes. Experimentally the cause and effect relationship of abrupt changes in the interplanetary medium and SC's has been demonstrated more recently with measurements from satellites in the interplanetary medium, Sonnet et al. (1964) and Gosling et al. (1967).

The sudden commencement phase of a magnetic storm is thus one of the few events involving the dynamics of the magnetosphere which is fairly well understood and this is a good phenomena to begin to study with a satellite borne electric field experiment in order to gain confidence in the experimental accuracy since the rapid increase in magnetic field can be related directly to a known electric field by means of Maxwell's third equation

$$\nabla \times \vec{E} = \frac{-\partial \vec{B}}{\partial t} \tag{1}$$

This equation is valid independently of the properties of the plasma and the electric field thus observed in the outer magnetosphere can be interpreted to a large degree independently of a number of hard problems such as parallel electric fields, reference frames, and magnetic drifts corrections which are not very well understood at present.

During the later half of 1972 there were two sudden commencements which occurred when the IMP 6 satellite was well within the magnetosphere. The first of these occurred during the period of large solar disturbances in early August which produced a number of spectacular phenomena at ground level. During the SC at 20:54 on August 4 (Figure 1) the IMP 6 satellite which carried the electric field experiment and the ATS-5 satellite which carries a magnetometer were both at altitudes of about 7 r_E (Figure 2). This SC produced increases in horizontal magnetic fields of the order of 40 γ at low latitudes and much higher perturbations at auroral latitudes (Figure 1). This sudden commence has been identified with a solar flare which occurred two days earlier at about 20 hours U.T. on August 2 in the McMath region of the solar disc (S.G.D. Sept. 2, 1972).

Magnetic field data from the ATS-5 satellite is especially useful in describing the motions of the magnetosphere during this event since it is near the equator where a considerable amount of such data has been analyzed in terms of motions of the magnetopause; Nishida and Cahill (1964), Patel and Coleman (1968), Skillman and Sugiura (1971). We will spend most of the efforts in this report analyzing this one event in considerable detail including the morphology of the SC from ground observatory data. The second SC which we report here occurred when the IMP 6 satellite was inside the plasmapause at 3 r_E near the equator. We do not have satellite magnetometer data for this event and the electric field data is included here simply to show that characteristics of the electric fields observed during this event is very similar to the first SC which occurred when IMP 6 was considerably further out in the magnetosphere. The plasma density and temperature at the locality of IMP 6 was probably orders of magnitude different for these two SC, yet the observed electric field variations were very similar.

SATELLITE MEASUREMENTS OF MAGNETIC FIELD

The ATS-5 satellite is in a synchronous orbit which is geostationary at +10° magnetic latitude and 255° east geographic longitude (Table 1). Description of the magnetometer and previous results from the ATS-5 experiment have been described in a number of papers by Skillman and others (Skillman 1970, 1972 and Skillman and Sugiura 1971). Twenty-four hours of ATS-5 measurements of Bz (north component) are shown in Figure 1 and a plot of the sudden commencement with better temporal resolution is shown in Figure 3 for the period 20:40 to 21:05 showing the increase in Bz of the sudden commencement to be discussed here. We estimate the motion of the magnetopause which accompanies this increase in $\vec{B}$ from Mead's model (Mead 1964) of the magnetosphere to correspond to inward motion from about 8 R_E to about 6.9 R_E at the sub-solar point (see

Skillman and Sugiura, 1971). These numbers are only very approximate, however, since the magnetosphere was in a storm phase at the time of this sudden commencement and the curl free Mead model of $\vec{B}$ neglects the contribution from ring current plasmas this ring current was appreciable at this time. Sugiura and Poros (1972) report some 60 γ of the hourly Dst index during this period.

D.C. ELECTRIC FIELD EXPERIMENT

The Explorer 33 satellite which carried the D.C. electric field experiment is one of the series of interplanetary monitoring platforms which are spin stabilized spacecraft with the axis of rotation perpendicular to the solar ecliptic plane. The sensors for the d.c. electric field experiment are long unfurlable antennas. One pair was extended 91.5 m (300 ft) tip-to-tip and a shorter pair was extended 45.7 m (150 ft) tip-to-tip. The antennas were shared with a number of other a.c. electric field experiments. The inner portion of the antennas had an insulative coating to remove the active areas away from the plasma sheath region of the spacecraft. The actual active areas of these probes were thus 75 meters for the longer pair (x) and 35 meters for (y) pair. See Aggson (1969) for a description of the double-floating probe technique as applied to such long antenna sensors.

The accuracy of this experiment varies from region to region but beyond the plasmapause seems to be about .5 mv/meter for the longer (Y) pair and 4 mv/meter for the X pair.

The active antenna lengths (2) have been calibrated when the satellite was near perigee from the $\vec{V} \times \vec{B}$ electric field induced by the satellite motion and found to be close to their geometrical values. The d.c. voltages $V_1 - V_2$ on the antennas are monitored with high impedance preamplifiers which are then subtracted with a precision d.c. amplifier to yield $\vec{E}$, Aggson (1969).

$$\vec{1} \cdot (\vec{E} + \vec{V} \times \vec{B}) = (V_1 - V_2) \qquad (2)$$

The $\vec{V} \times \vec{B}$ correction in this expression for the orbital motion o .e sate. . was only about 0.2 mv/meter at the location of the satellite during the first sudden commencement and can be neglected for the measurements of that event. During the SC of October 1922 the V × B correction was 3 mv/meter.

D.C. ELECTRIC FIELD MEASUREMENTS

The magnetospheric electric fields measured during the period of the first sudden commencement is shown in Figure 4. The measurements shown represent 10.3 sec averages of a least squares sine wave fit to the spin modulation of the electric field vector measured in the ecliptic planes. The component of E which is plotted here is only the X component of $\vec{E}$ in solar ecliptic coordinates. The y component of $\vec{E}$ was quite small during this period (< 1 mv/meter) as was expected since the magnetic field vector should lie roughly in the -y direction at the magnetospheric position of the satellite at the time of the sudden commencement. Comparing the values of satellite measurements of Ex (Figure 4) with Bz (Figure 3) shows that the initial disturbance in both measurements which occurred within about one minute of 20:54 UT on August 4, 1972. We will show later that Ex is related to a first approximation to the time derivative of Bz during the initial part of this event.

ACCURACY OF THE ELECTRIC FIELD MEASUREMENTS

As mentioned earlie · we have gained considerable experience in the accuracy of this experiment by fitting measured values of $\vec{E}$ with calculation of $\vec{V} \times \vec{B}$ associated with orbital motion during magnetically quiet satellite crossings through the magnetosphere. The accuracy is limited by contamination of d.c. electric fields in the sheath of the satellite. In the outer magnetosphere the 35 meter sensor pair has an accuracy of some millivolts/meter and the 75 meter sensor pair is about an order of magnitude more accurate. At 20:55 UT on Figure 4 the measured electric field was 10 mv/meter on both pair of antennas. This condition of both antenna pairs yielding the same answer is a stringent condition since sheath errors fall off exponentially as a function of the distance of the active areas of the probes from the satellite. We feel extremely confident that the measurements from the Y antenna pair are accurate to within ±1 mv/meter and about ±20° azimuthal uncertainty at the time of this initial increase in E. At 20:57 UT where the measured Ex has reversed in phase, the plasma p[illegible]eters which affect the sheath errors seems to have changed appreciably an[illegible] agreement is only to within about ±2 mv/meter between the two sensor pairs. The accuracy of these measurements is thus not as g[illegible]at as would be desired, but they should allow a quantative interpretation of this event to within perhaps 10%. In the second event to be discussed here the satellite is inside the plasmapause during the SC and the sheath errors are an order of magnitude smaller since the Delze screening distance is considerably smaller inside the plasmapause.

GROUND LEVEL OBSERVATIONS

In Figure 5 we have plotted the H component of magnetometer records from three observatories, near the noon meridian at the time of the first sudden commencement. The low-latitude measurements (Honolulu) are quite similar to equatorial satellite magnetometer record of ATS-5 with the 40γ compression occurring about 2 minutes later at ground level than at synchronous altitudes. The observations at auroral zone latitudes from Alaska (College and Barrow) show much larger magnetic disturbances and oscillatory temporal variations quite similar to the SC's studied by Wilson and Sugiura (1961). These authors analyzed these high latitude variations as transverse eliptically polarized Alfven waves propagating from an initial disturbance in the outer magnetosphere. These high latitude magnetic perturbations are also similar to the electric field oscillations observed on IMP 6 (Figure 4). The records from four low latitude observations are shown in Figure 6. These records are included here to demonstrate the world wide character of the sudden increase in Δ H during the first disturbances of the SC.

The ground station magnetic field measurements shown in Figures 5 and 6 were obtained by digitizing observatory normal, storm and rapid run magnetograms and replotting the measurements with common time and magnitude scales.

INTERPRETATION OF THE SATELLITE MEASUREMENTS

The time derivative of the magnetic field vector is related to the electric field via Maxwell's equation:

$$\vec{\nabla} \times \vec{E} = \frac{-\partial \vec{B}}{\partial t} \tag{2}$$

The static or equilibrium contribution to the magnetospheric magnetic field $\vec{B}$ from the surface currents at the magnetopause has been treated by Beard (1964), Mead and Beard (1964) and others. We will use only the first two terms in the expansion of Mead (1964):

$$B_x = -2.1\, z\, R^{-4} \tag{3}$$

$$B_y = 0 \tag{4}$$

$$B_z = 24R^{-3} + 2.1 \times R^{-4} \tag{5}$$

where x, y, and z are in units earth radii, R is the distance to the magnetopause boundary at the sub-solar point in units of 10 earth radii and $\vec{B}$ is in units of gamma (10^{-9} mks).

We will attempt a quasi-static model of the magnetosphere for the period during the sudden commencement:

$$B_x(t) = -2.1\, z\, R^{-4}(t) \tag{6}$$

$$B_y(t) = 0 \tag{7}$$

$$B_z(t) = 24\, R^{-3}(t) + 2.1 \times R^{-4}(t) \tag{8}$$

The approximation of Equations (6)-(8) neglects the finite propagation times of the magnetic disturbance from the magnetopause and in addition this approximation assumes that general shape of the magnetopause remains the same during the compression. We have attempted to document the validity of this later assumption with Figures 3 and 6 where the SC was shown to a first approximation to be a magnetospheric wide uniform increase in Bz of about 40γ.

In order to solve for E (t) we shall express the magnetic field vector in terms of a vector potential:

$$\vec{B}(t) = \vec{\nabla} \times \vec{A}(t) \tag{9}$$

where

$$A_x = -12\, R^{-3}(t)\, y \tag{10}$$

$$A_y = +12\, R^{-3}(t)\, x + 1.05\, R^{-4}(t)\, (z^2 + x^2) \tag{11}$$

$$A_z = 0 \tag{12}$$

seems the most elementary solution to Equations 6, 7 and 8.

Since

$$\vec{E} = \frac{-\partial \vec{A}}{\partial t} \tag{13}$$

we have

$$E_x = 12\, y \frac{\partial}{\partial t} (R^{-3}) \tag{14}$$

$$E_y = -12\, x \frac{\partial}{\partial t} (R^{-3}) - 1.05\, (z^2 + x^2) \frac{\partial}{\partial t} (R^{-4}) \tag{15}$$

and

$$E_z = 0 \tag{16}$$

Equation 14 can be approximated in a more familiar form

$$Ex \simeq \frac{1}{2}\, y \frac{\partial Bz}{\partial t} \tag{17}$$

which is simply the elementary equation for uniform induction with circular symmetry about the z axis.

The approximation of Equation (17) describes fairly well the relationship between the world wide increase of Bz during the SC as observed on ATS-5 and the initial electric field disturbance of the SC as observed on IMP 6. It predicts a negative value of Ex (anti solar) during compression of the magnetosphere. In Figure 7 we have compared Bz (t) as observed on ATS-V (top curve) with Ex (t) as observed on IMP 6. The circles on these graphs represent the data and the curve Bz (t) and Ex (t) are a fit to Equation (17). Except for the 58" delay (in SE coordinates the ATS-5 satellite is about twice as far towards the sun as was IMP 6 at the time of this SC), this analytical treatment seems to describe fairly well the relationship between these observations. We consider this agreement essentially a calibration of double floating experiment in outer magnetosphere.

After the initial increase in $\vec{E}$, which is an azimuthal vector, the observed electric field rings several times with a period of about 3 or 4 minutes. This oscillation of $\vec{E}$ is similar to magnetic disturbance H observed at the observatory at Barrow which is near the foot of the magnetic vector through Explorer 38 at the time of this SC, see the bottom curve (c) of Figure 7, and the top two curves of Figure 5. As mentioned in the introduction, Wilson and Sugiura (1961) first interpreted the oscillations as transverse hydromagnetic waves propagating from an initial disturbance in the outer magnetosphere along magnetic field lines. Since our analysis of the measured magnetospheric electric field has yielded an analytical function of this initial disturbance.

$$E_x \simeq \frac{\partial A_x}{\partial t} = \frac{1}{2} y \frac{\partial Bz}{\partial t} \tag{17}$$

We should be able to follow analytically the disturbance vector along the magnetic (dipole) field lines from the equatorial region to the ionosphere. We will assume this propagation is essentially the transverse Alfvén mode where to a first approximation the plasma moves to the magnetic field and the disturbance vectors are related simply by the expression

$$\vec{E}(t) = -\vec{V}_A \times \vec{B}(t) \tag{18}$$

As the disturbance vectors propagate inward towards the ionosphere the convergence of magnetic dipole field lines will amplify the disturbance vectors considerably. We will estimate this amplification by assuming continuity of magnetic lines of force

$$\left.\begin{array}{ll} r \simeq \dfrac{L}{\cos\theta} & , \text{ r in earth radius} \\ \phi \simeq \text{constant} & , \theta = \text{magnetic latitude} \end{array}\right\} \tag{19}$$

We estimate the amplification factor for this converge from the equator to the ionosphere as simply the inverse of the distance Δd between adjacent lines of force

$$A = \frac{\Delta d\,(R = L,\ \theta = 0)}{\Delta d\,(R \simeq 1,\ \theta \simeq 0)} \tag{20}$$

which for the dipole equations is to a first approximation

$$A \simeq 2L^{3/2}, \text{ poloidal polarization}$$

$$A \simeq L^{3/2}, \quad \text{torsional polarization}$$

or even more approximately

$$A \simeq 1.5 L^{3/2} \tag{21}$$

Here L is the equatorial radius of the magnetic dipole vector in units of earth radii.

With this approximate amplification factor it is a straightforward process to extrapolate the initial electric field disturbance Ex (t) as measured on IMP 6 to the ionosphere. If we then assume the Ex (t) drives an ionosphere sheet current system with an integrated conductivity $\int \sigma \, dt \simeq 1\gamma/\text{mv/meter}$ we get a fairly quantative agreement with the disturbance vector H near the foot of the field line at Barrow, Figure 7c. After this initial change in Bi at Barrow the H disturbance vector is seen in Figure 7 to oscillate convincingly similar to the disturbance Ex (t) on IMP 6. We consider this similarity a direct experimental confirmation of the original thesis of Wilson and Sugiura (1961) as mentioned earlier.

We have scaled the horizontal disturbance vectors from a number of ground level observatories during this SC, Table I, and in Figure (8) where we have plotted these amplitudes as a function of geomagnetic latitude. In Figure 8 we have also plotted the product of the extrapolated electric field vector Ex (L) times the integrated conductivity

$$\Delta H = A\sigma \left\{ \frac{1}{2} \frac{\Delta B}{\Delta t} \right\} + 40\gamma \tag{22}$$

where

$$\frac{\Delta B}{\Delta t} \simeq \frac{40\,\gamma}{40 \text{ sec}} \simeq 10^{-9} \text{ mks}$$

for the SC.

Equation 22 above is seen in Figure 8 to describe fairly well the amplitude of the initial disturbance H of the sudden commencement as a function of latitude.

POLARIZATION OF THE INITIAL DISTURBANCE

As mentioned earlier the electric field vector observes at the time of the SC on IMP 6 oscillated in the ±x direction (SE coordinates). If this event was elliptically polarized, the other component of E (t) would have been roughly in the z direction where we do not have electric field measurements. If you consider the morphology of the Δ H disturbance in the northern hemisphere below $\lambda_m \simeq 70°$, these disturbance vectors are for the most part in the +z or northernly direction as can be seen in Figure 9. If we interpret these magnetic disturbances as originating mainly from Hall currents in the ionosphere, the electric field driving this current distribution is northward in the northern ionosphere. Thus the azimuthal equatorial disturbance $\vec{E}x$ seems to have rotated about 90° to produce the initial disturbance in the ionosphere. This is neither pu~ely a poloidal nor purely torsional mode but it might represent another type of standing wave, perhaps a hybrid of these two modes for which we can find no reference in the literature.

MEASUREMENTS DURING THE SC OF OCT. 18, 1972

At 17:46 UT on Oct. 18, 1972 another disturbance with similar damped oscillations was observed on IMP 6 when the satellite was inside the plasmapause at

$r = 3\ R_E$, $\lambda_m = +2°$ at about 11:00 geomagnetic time. A worldwide SSC was reported at this time by a large number of ground level observatories, the nearest of these to the foot of the field line of IMP I was Fredericksburg which reported an increase of some 21 γ in H for the SC. The electric field measurements from IMP 6 and the ΔH observations from Fredericksburg are compared in Figure 10. Here we have plotted the total amplitude of $\vec{E}$ in the spin plane (SE) of IMP 6 and we have not included the subtraction of the $\vec{V} \times \vec{B}$ orbital correction which was appreciable here (3 mv/meter). The azimuthal variation of the $\vec{E}$ vector measured here was mainly in the -y direction during this entire period indicating a magnetosphere azimuthal electric field in the counterclockwise direction during this SC similar to the measurements reported above for the SC of August 4, 1972.

DISCUSSION AND CONCLUSIONS

The double floating probe experiment carried aboard IMP 6 seems to have sufficient accuracy (~1 mv/meter) to measure the induction fields during the compression of the magnetosphere during the two sudden commencements reported here. We have analyzed these events analytically rather than attempting to count magnetic field "lines" as they passed the satellite during these sudden commencements because we were able to treat these electric fields from first principles without too much effort. The oscillatory behavior of the magnetosphere after the initial disturbance of the SC, i.e., the ringing of the observed electric fields, seems to show up much better in these direct electric field measurements in contra distinction to satellite borne magnetometers which have not reported such oscillatory behavior in association with this type of event.

We have not analyzed yet the data from the magnetometer carried aboard IMP 6. We estimate that the magnitude of B was greater than the 400 γ ranges of that instrument for these two events; however, for the analysis presented in this paper only the general magnetospheric wide variations in $\vec{B}$ were of significance and the local value of $\vec{B}$ at the satellite position where the observations of E were taken is not critical for the treatment. It should be possible to estimate the local magnitude of the hydrodynamic oscillations in $\vec{B}$ generated after the critical disturbances from the IMP 6 magnetometer data, and from the ratio of $\Delta\vec{E}$ to $\Delta\vec{B}$ estimate the local plasma density at these locations.

REFERENCES

Aggson, T. L., Probe measurements of electric fields in space in Atmospheric Emissions, edited by B. M. McCormac and A. Omholt, pp. 305, Van Norstrand Reinhold, New York, 1969.

Beard, D. B., The solar wind geomagnetic field boundary, Rev. Geophys., 2, 335-365, 1964.

Chapman, S., and J. Bartels, Geomagnetism, Clarendon Press, Oxford, 1940.

Chapman, S., and V. C. A. Ferraro, A new theory of magnetic storms, Terrestrial Magnetism and Atmospheric Elec., 36, 77-97, 171-186, 1931; 37, 147-156, 421-429, 1932; The theory of the first phase of a geomagnetic storm, Terrestrial Magnetism and Atmospheric Elec., 45, 245-268, 1940.

Dessler, A. J., The propagation velocity of worldwide sudden commencements of magnetic storms, J. Geophys. Research, 63, 405-408, 1958.

Gold, T., in Gas Dynamics of Cosmic Clouds, Chap. 17, p. 103, North-Holland Publishing Company, Amsterdam, 1955.

Gosling, J. T., J. R. Asbridge, S. J. Bame, A. H. Hundhausen, and I. B. Strong, Discontinuities in the solar wind associated with sudden geomagnetic impulses and storm commencements, J. Geophys. Res., 72, 3357, 1967.

Mead, G. D., and D. B. Beard, Shape of the geomagnetic field solar wind boundary, J. Geophys. Res., 69, 1169, 1964.

Mead, G. D., Deformation of the geomagnetic field by the solar wind, J. Geophys. Res., 69, 1181-1195, 1964.

Nishida, Atsuhiro, and L. J. Cahill, Jr., Sudden impulses in the magnetosphere observed by Explorer 12, J. Geophys. Res., 69, 2243, 1964.

V. L. Patel and P. J. Coleman, Jr., Sudden Impulses in the Magnetosphere Observed at Synchronous Orbit. J. Geophys. Res. 75, 7255, 1970.

Skillman, T. L., and M. Sugiura, Magnetopause crossing of the geostationary satellite ATS-5 at 6.6 R_E, J. Geophys. Res., 76, 44-50, 1971.

Skillman, T. L., ATS-E Magnetic Field Monitor Instrumentation, GSFC Document X-645-70-54, January 1970.

Sonett, C. P., and D. S. Colburn, The si$^+$ - si$^-$ pair and interplanetary forward-reverse shock ensembles, Planetary Space Sci., 13, 675, 1965.

Sonett, C. P., D. S. Colburn, L. Davis, Jr., E. J. Smith, and P. J. Coleman, Jr., Evidence for a collision-free magnetohydrodynamic shock in interplanetary space, Phys. Rev. Letters, 13, 153, 1964.

Sugiura, M., A sudden change in the solar wind pressure and the outer region of the magnetosphere, J. Geophys. Res., 70, 4151, 1965.

Sugiura M., and D. J. Pores, Provisional hourly values of equatorial Dst for July, August, September and October 1972, GSFC Document X-645-73-18, January 1973.

Wilson, C. R., and M. Sugiura, Hydromagnetic interpretation of sudden commencements of magnetic storms, J. Geophys. Res., 66, 4097-4111, 1961.

Wilson, C. R., and M. Sugiura, Discussion of our earlier paper 'Hydromagnetic interpretation of sudden commencements of magnetic storms,' J. Geophys. Res., 68, 3314-3320, 1963.

TABLE I
SUDDEN COMMENCEMENT — 4 AUGUST 1972 — 2100 UT

STATION	GEOGRAPHIC LATITUDE (N)	GEOGRAPHIC LONGITUDE (W)	GEOMAGNETIC LATITUDE (N)	GEOMAGNETIC LONGITUDE (E)	MAGNETIC TIME (HOURS)	S.C. AMPLITUDE (GAMMA)	COMPONENT
RESOLUTE	74.7	94.9	83.1	287.7	11.98	–645	X
MOULD BAY	76.2	119.4	79.1	284.7	9.74	–182	X
CAMBRIDGE	69.1	105.1	76.7	355.8	12.31	1200	H
BAKER LAKE	64.3	96.0	73.9	314.8	13.69	1012	X
CHURCHILL	58.8	94.1	68.8	322.5	14.18	782	X
BARROW	71.3	156.8	68.5	241.1	8.71	737	H
GREAT WHALE	55.3	77.8	66.8	347.2	15.82	153	H
COLLEGE	64.5	147.8	64.6	256.5	9.74	250	H
MEANOCK	54.6	113.3	61.8	301.0	12.73	89	H
SITKA	57.1	135.3	60.0	275.4	11.00	110	H
OTTAWA	45.4	75.6	57.0	351.5	16.09	80	H
NEWPORT	48.3	117.1	55.1	300.0	12.66	62	H
VICTORIA	48.5	123.4	54.3	292.7	12.18	50	H
TUCSON	32.2	110.8	40.4	312.2	13.46	39	H
SAN JUAN	18.1	66.1	29.6	3.1	16.85	50	H
KAKIOKA	36.2	219.8	26.0	206.0	6.37	64	H
HONOLULU	21.3	158.0	21.1	266.5	10.41	48	H
GUAM	13.6	215.1	4.0	212.9	6.83	56	H
PORT MORSEBY	–9.4	212.1	–18.6	217.9	8.16	65	H
HERMANUS	–34.4	340.8	–33.3	80.5	22.01	52	H
GNANGARA	–31.8	244.1	–43.2	185.8	5.03	60	H
TOOLANGI	–37.5	214.5	–46.7	220.8	8.37	70	H
ATS – 5	0.0	105.0	9.3	324.2	14.2	40	H
IMP 6	–32.3	193.8	–38.8	242.4	8.8	– –	– –

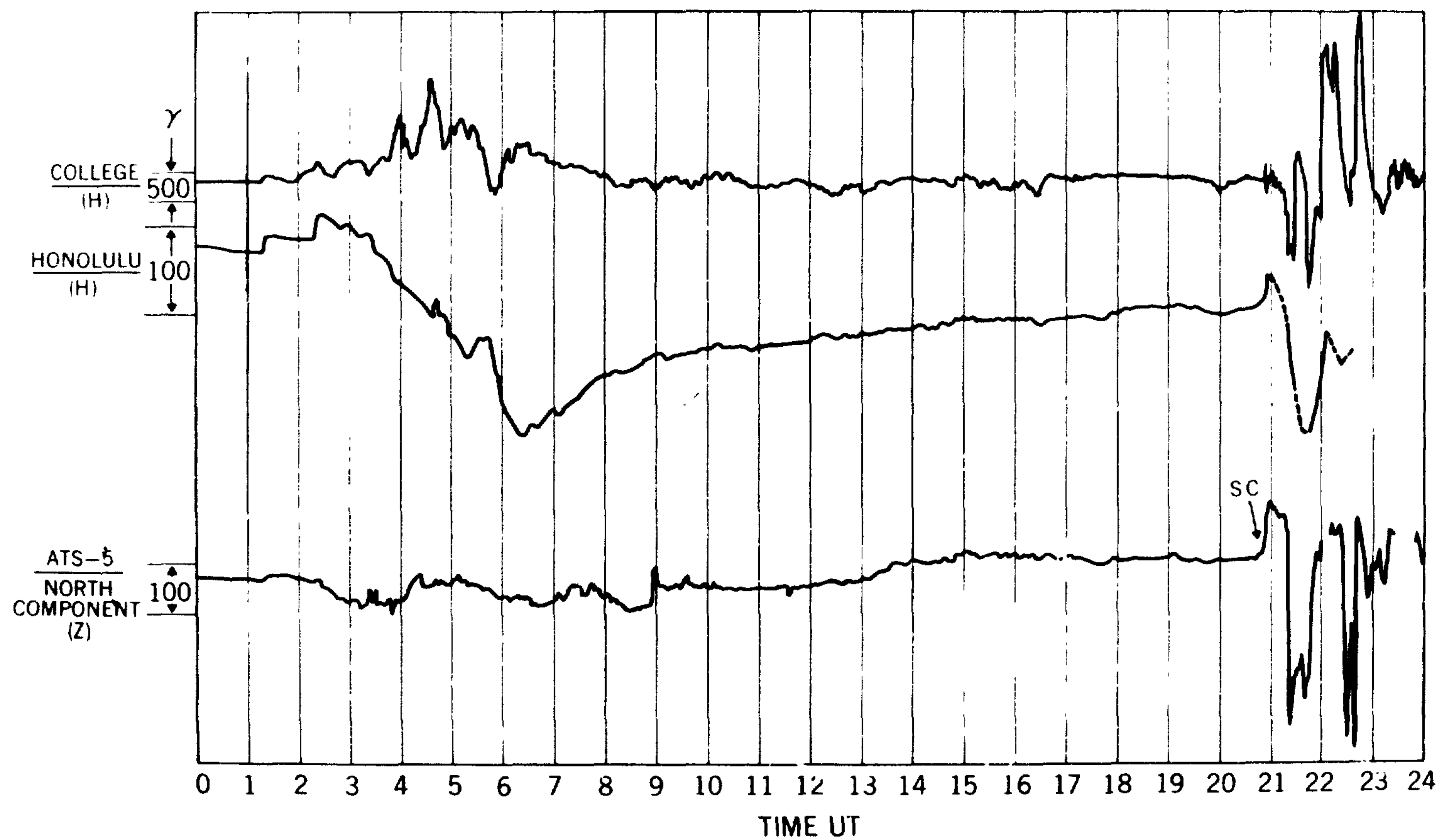

Figure 1. Magnetic field observations during August 4, 1972. Plotted here are the ΔH variations from two ground level observatories plus the main component (Z) from the magnetometer carried aboard ATS-5. The sudden commencement studied here occurred at 21:54 UT and is labelled SC.

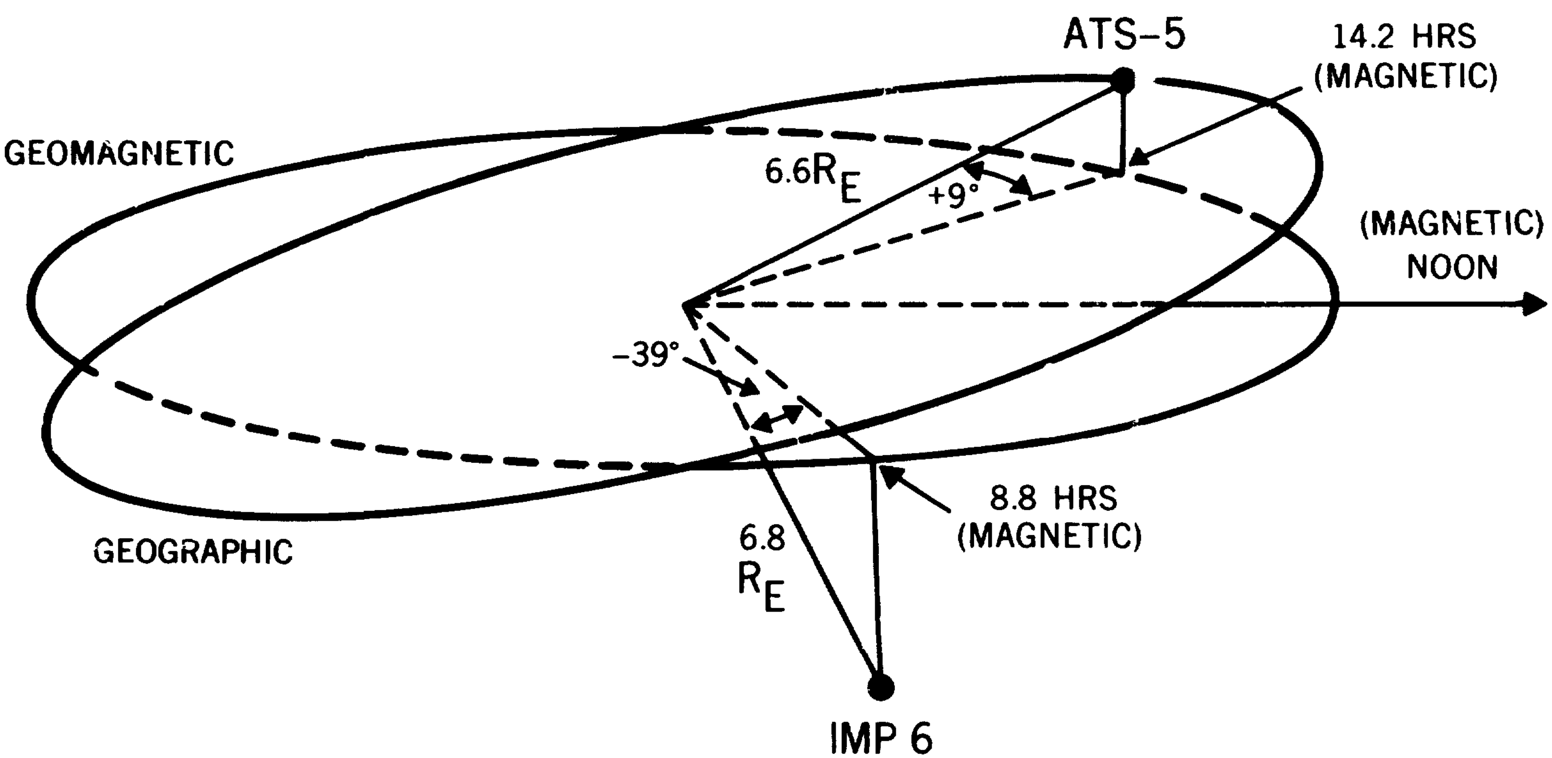

Figure 2. Locations of the ATS-5 and the IMP 6 satellites at 21:00 UT on August 4, 1972. Both satellites were near 7 R_E in the day hemisphere.

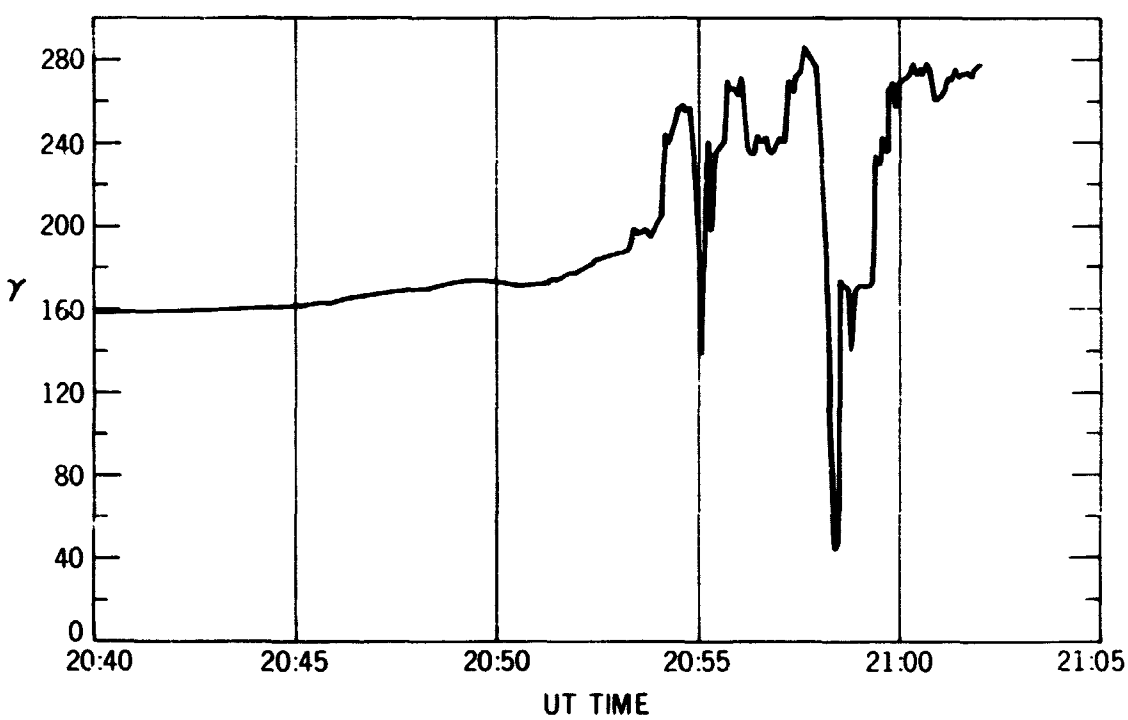

Figure 3. The (Z) component from the ATS-5 magnetometer with better temporal resolution during the SC.

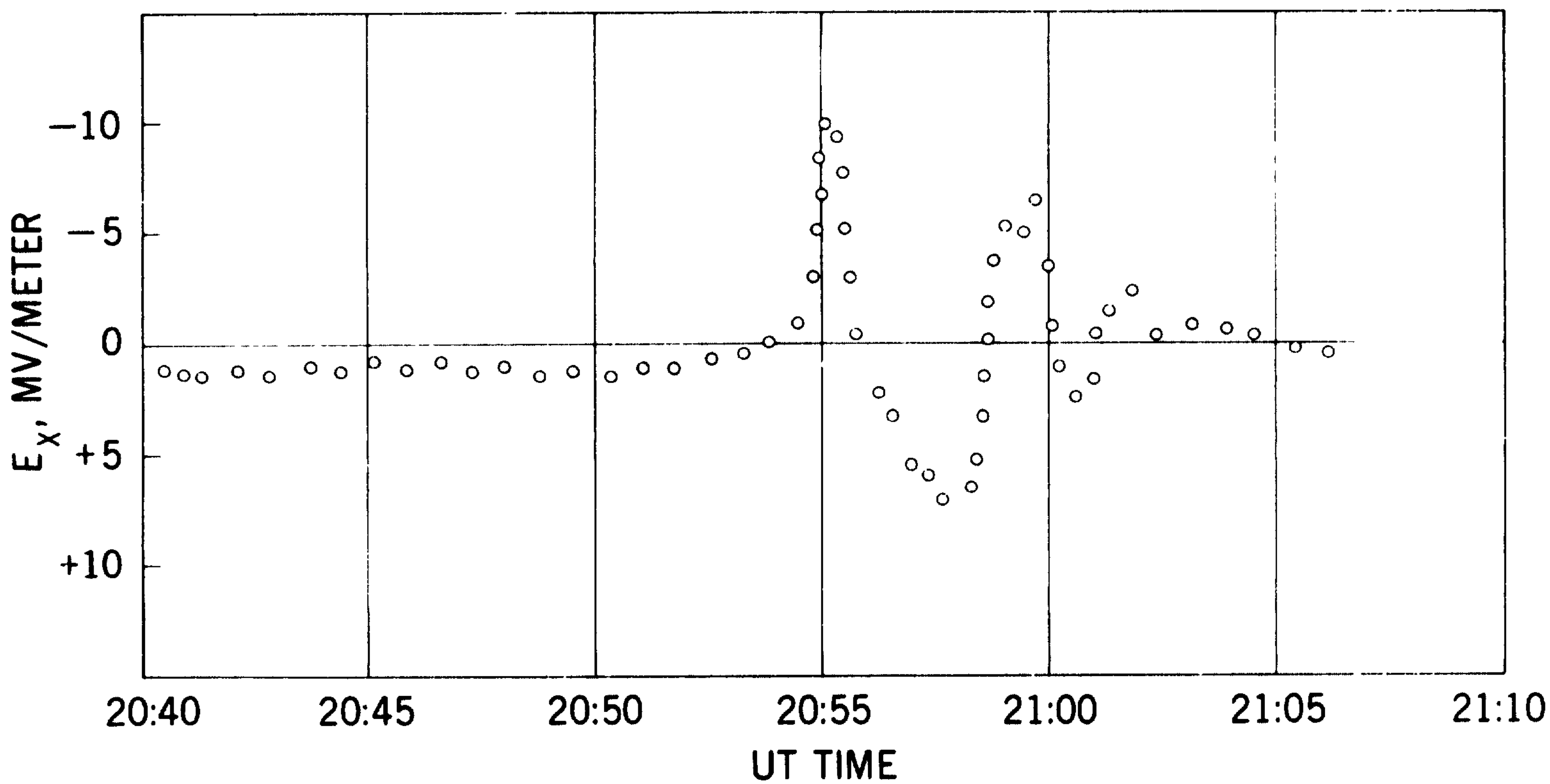

Figure 4. IMP 6 d.c. electric field measurements from 20:40 to 21:10, August 4, 1972. The X (SE coordinates) component of $\vec{E}$ is plotted here. The Y component of $\vec{E}$ was considerably smaller during this event.

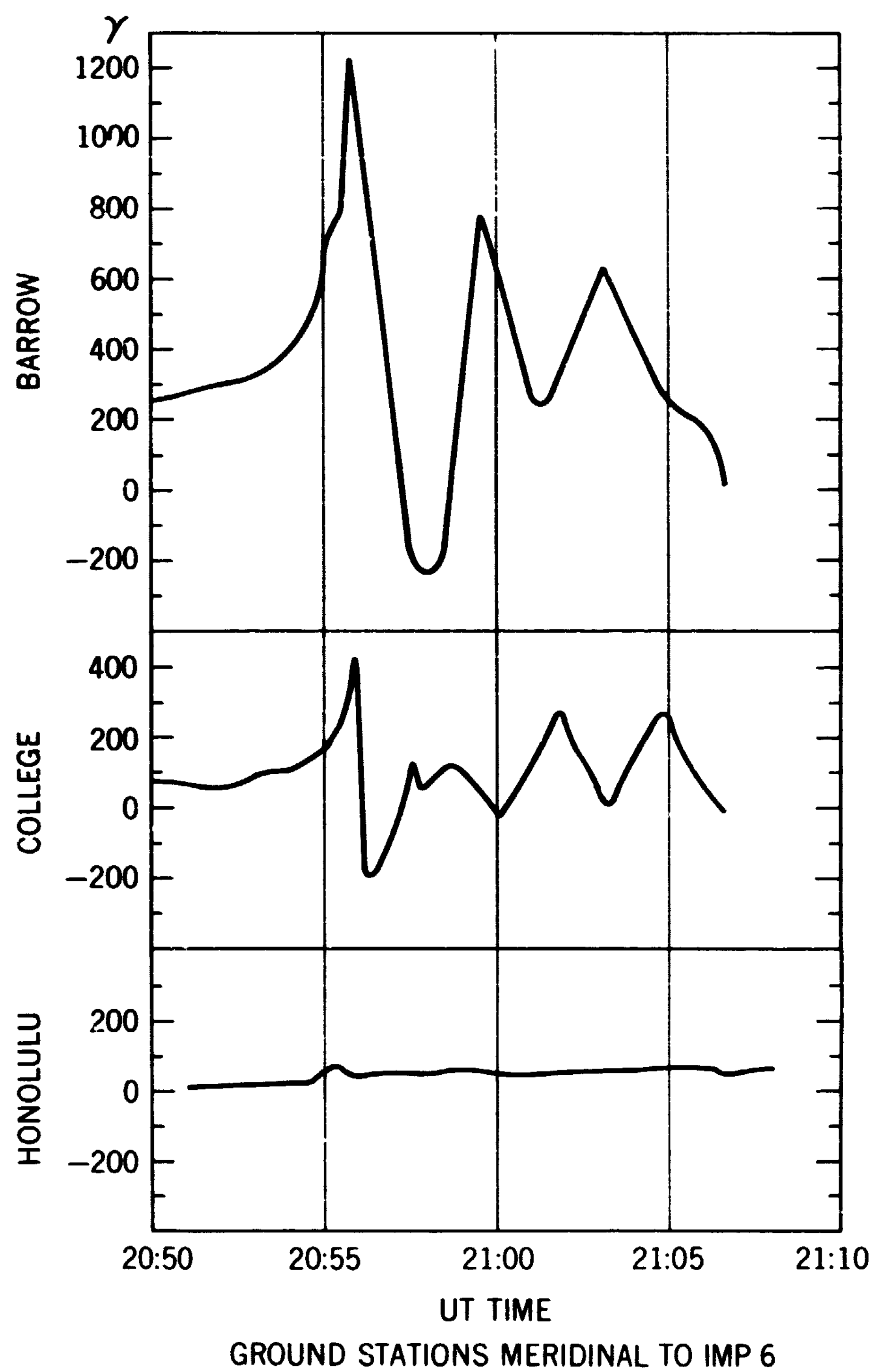

Figure 5. H trace of three magnetic observatories near the magnetic meridian of IMP 6 at 2100 on August 4, 1972. The temporal accuracy of the plots is not particularly good since these were scaled from regular and storm magnetograms.

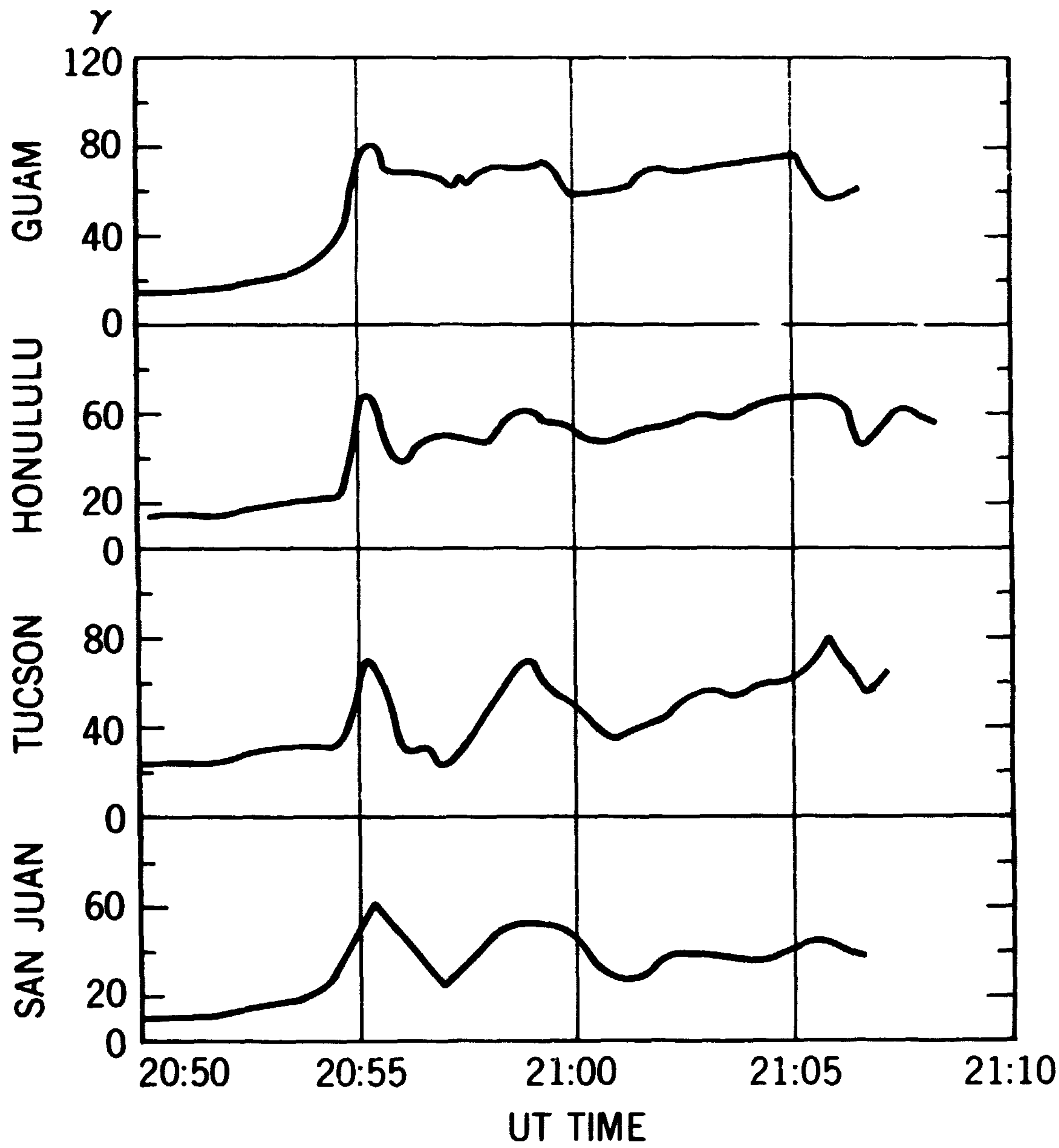

Figure 6. H trace from four low latitude observatories on August 4, 1972. These plots show the generally uniform worldwide increase in H at 20:55. Taken with Figure 3 these plots show a general magnetosphere wide uniform increase in Bz at the time of the SC.

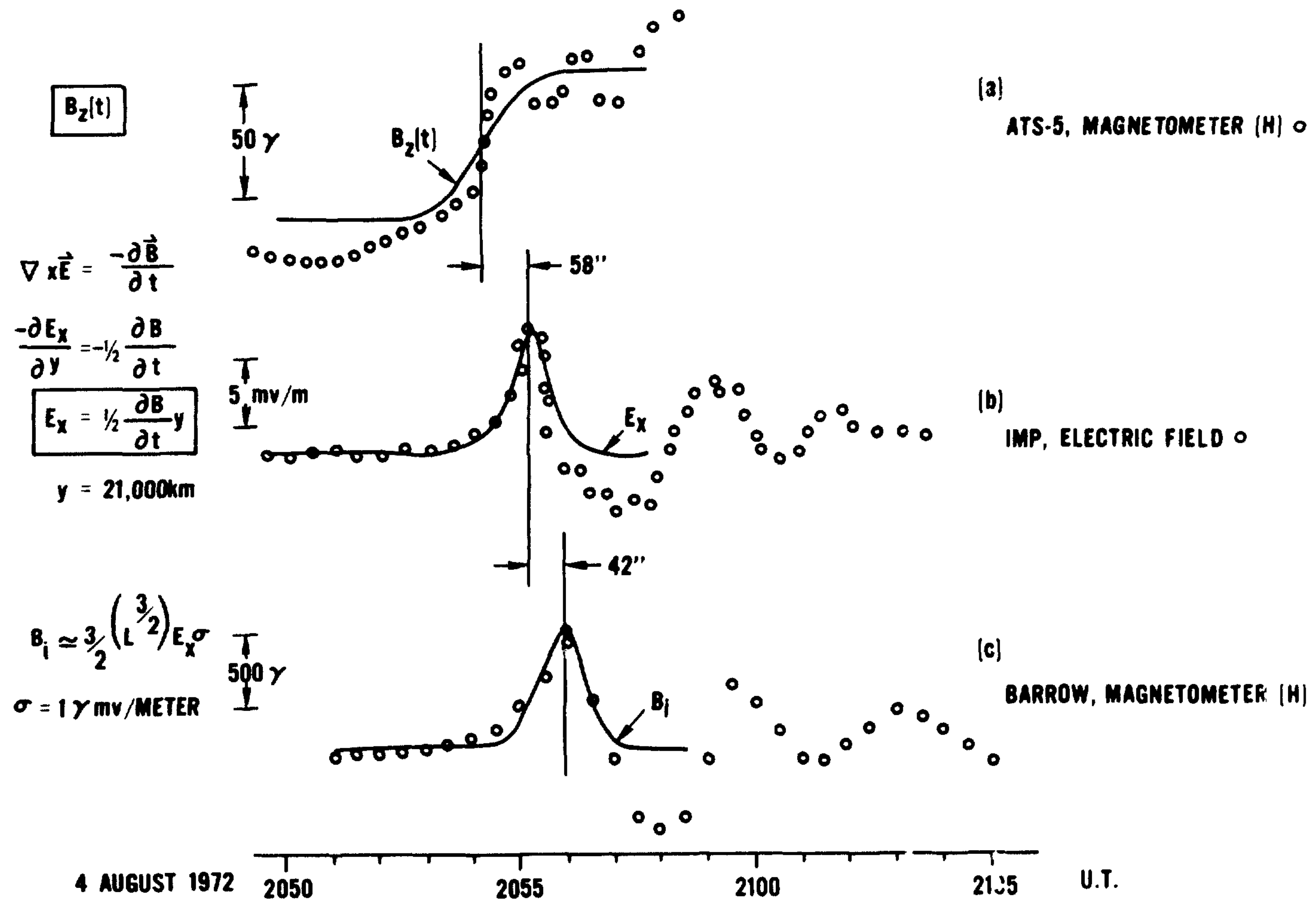

Figure 7. Comparison between ATS-5, IMP 6 and Barrow measurements during the sudden commencement at 20:54 August 4, 1972. As discussed in the text, the magnetosphere wide increase in Bz (curve a) induces an azimuthal electric field Ex in the outer magnetosphere (curve b) which propagates down the magnetic field vector to drive an ionospheric current which produces the ground level magnetic disturbance (curve c).

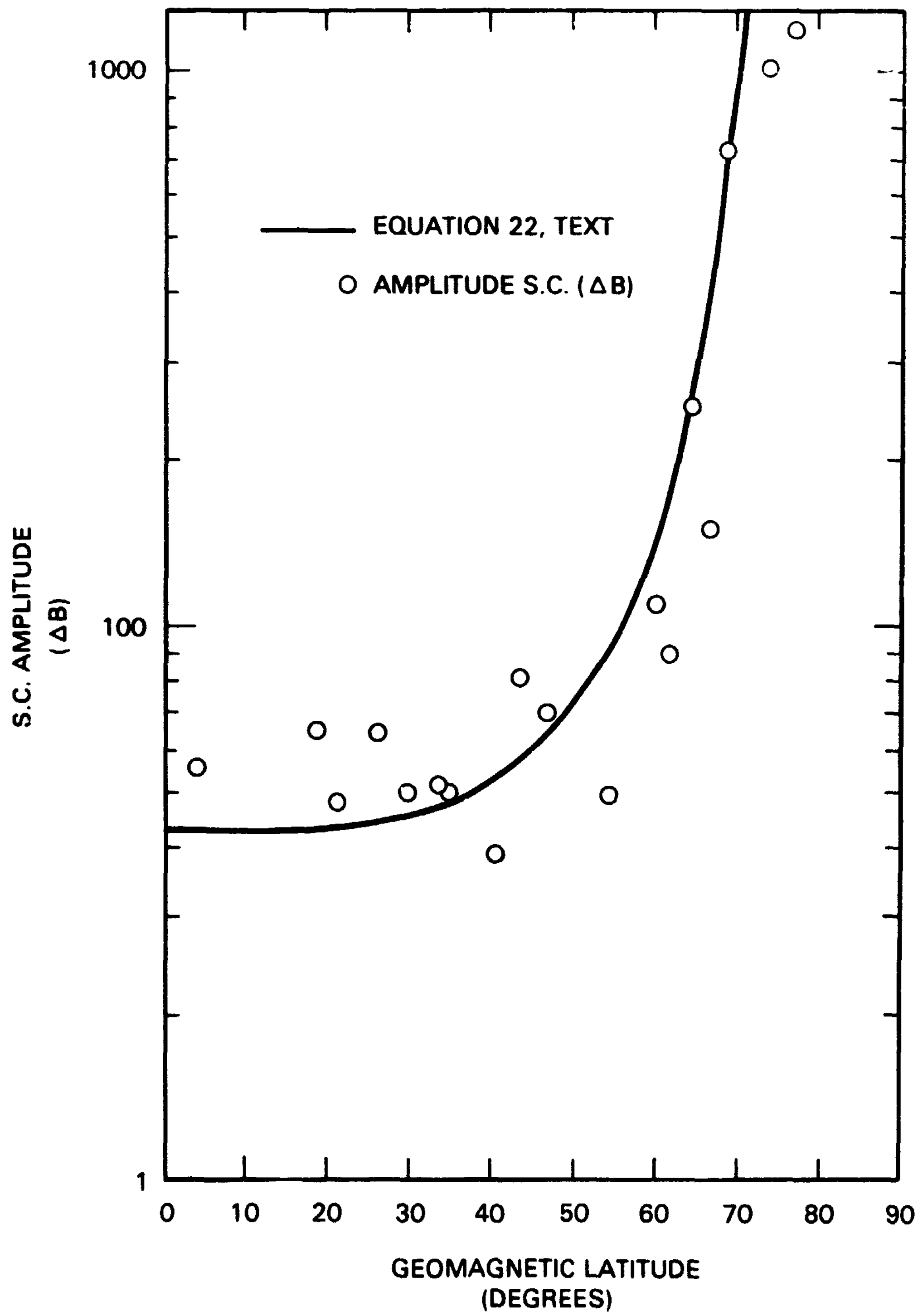

Figure 8. Latitude variation of the initial ground level magnetic disturbance of the SC on 20:54, August 4, 1972. The curve on this plot (Equation 22) has the same derivation as indicated step-wise on Figure 7.

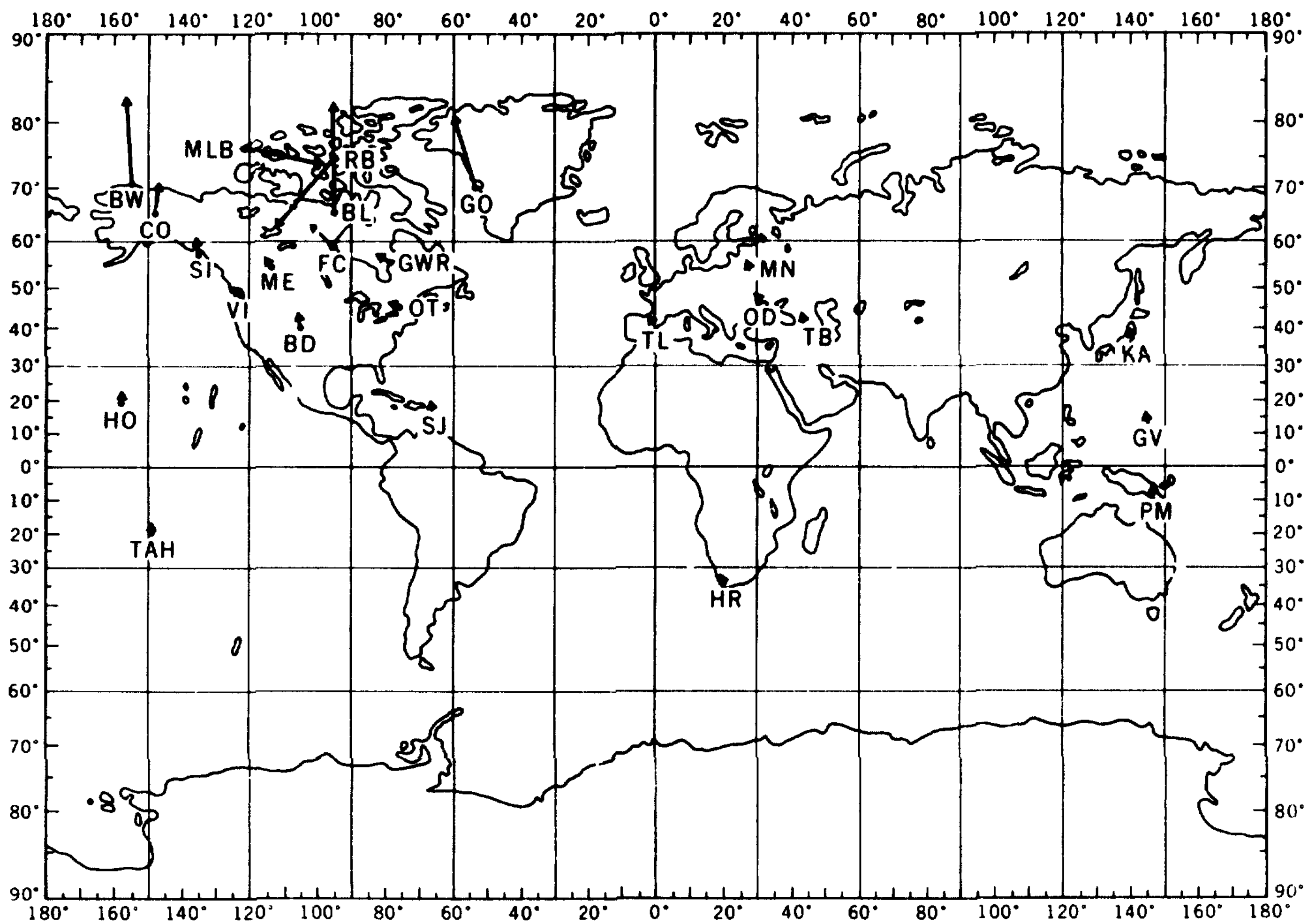

Figure 9. Horizontal disturbance magnetic vectors for SC of 20:54, August 4, 1972. The vector ΔH plotted here represents the direction of the maximum horizontal disturbance during the initial increase of H during the SC 20:54, August 4, 1972.

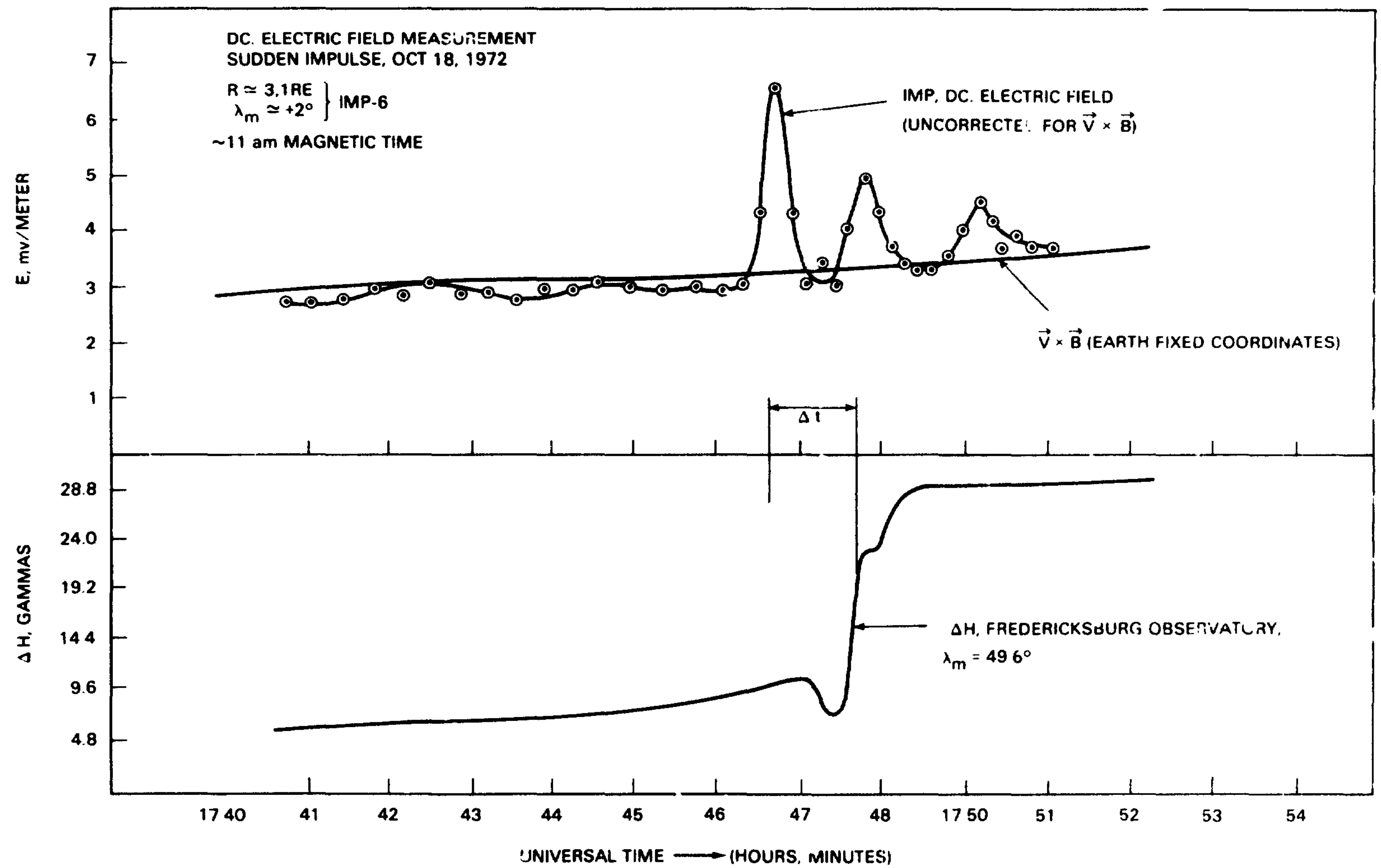

Figure 10. D.C. electric field measurements from IMP 6 and ΔH at ground level observatory near the foot of the field line of IMP 6 at 17:47, Oct. 18, 1972. At the time of this SC the IMP 6 satellite is inside the plasmapause.